# Observation of NLIW in the South China Sea using PIES

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## LONG-TERM GOALS

To study the mechanisms of generation, evolution and propagation of high frequency nonlinear internal waves [NLIW] in the vicinity and west of Luzon Strait in the South China Sea, making use of pressure equipped inverted echo sounders.

## OBJECTIVES

Our objectives are (1) to observe the internal tide propagating west of Luzon Strait and its progressive evolution in shape and speed as it traverses the South China Sea under the influence of nonlinearity, non-hydrostatic effects, rotation, topography, currents and stratification, and (2) to interpret the results with the help of models that incorporate these effects.

## APPROACH

Our approach involved deployment of three modified pressure equipped inverted echo-sounders [PIES], set up to transmit every 6s (see Fig.1).  These instruments measure the return acoustic travel time from sea-floor to surface, which is modified by variations in the local stratification resulting from passage of internal waves.  Knowledge of the background stratification is provided by CTD casts. Time series measurements of the acoustic travel time then provide a basis for inferring the first mode internal response. The observations are analyzed with 2-layer models: a weakly nonlinear and also a fully nonlinear model of the wave evolution process, a model of the wave generation mechanism and a coupled model in which the wave generation is coupled to the fully nonlinear evolution model.

## WORK COMPLETED

This project has now been completed. In addition to results from a pilot study in 2005, data were acquired from three instruments over the period April to October in 2007. The results have been analyzed as follows:

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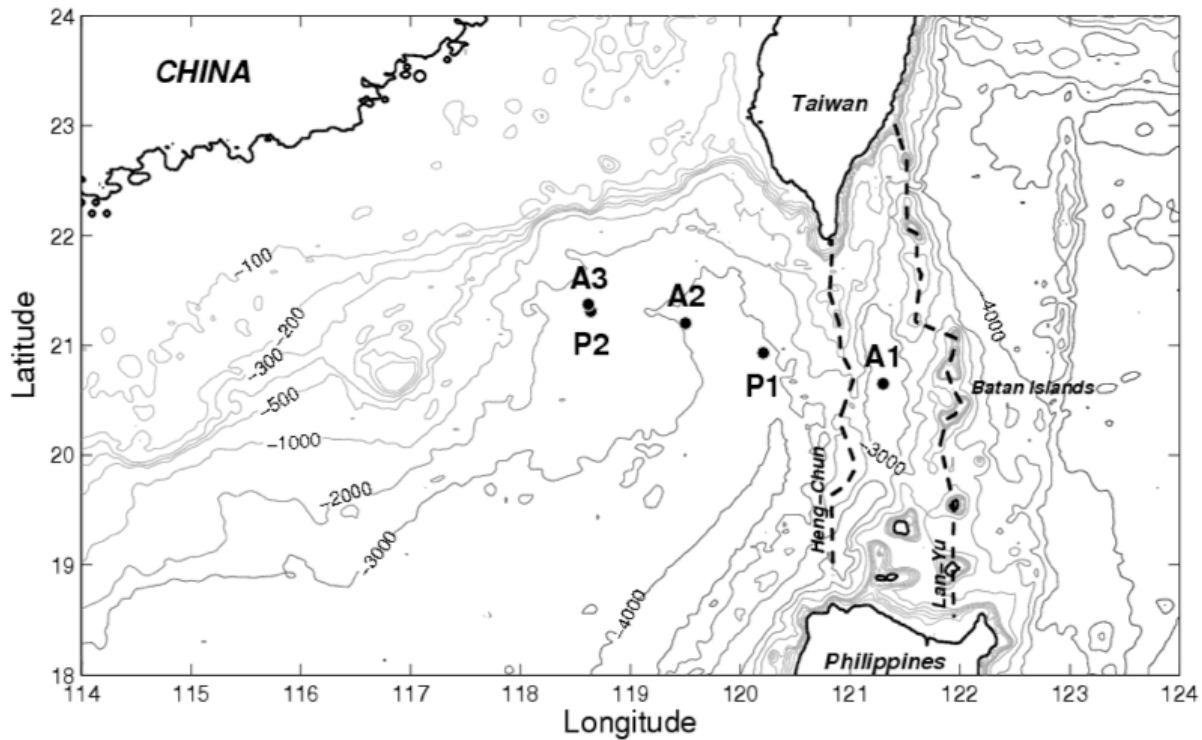Prescribed by ANSI Std Z39-18

***Fig 1: Chart of Luzon Strait showing deployments of inverted echo-sounders.***

(1) A model of the inverted echo-sounder instrument performance is published: Li et al. (*JAtmos&OcTech.,* 2009);

(2) Gerkema's (1996) 2-layer weakly weakly nonlinear model for generation and evolution of nonlinear internal waves was used to provide a preliminary analysis of the results, explaining some features of the waves, including their delayed formation. This work has been published by Farmer et al. (*Atmos-Ocean*, 2009);

(3) A linear generation model (Hibya, 1986) has been used to study the generation of internal tides from the two ridge topography of Luzon Strait;

(4) A coupled model in which Hibya's generation model is used to provide input to Helfrich's (1987) fully nonlinear evolution model was implemented and used to investigate the physical mechanisms underlying our observations. This work has been submitted for publication: Li & Farmer *(JPO).*

Key individuals involved in the NLIWI project include PhD student Li Qiang (URI), Karl Helfrich (WHOI), Tim Duda (WHOI), Jae-Hun Park (URI); Erran Sousa (URI), instrument deployments and recovery; Steve Ramp (MBARI) led cruises essential to the field program.

# RESULTS

1. Our model analysis of the inverted echo-sounder successfully described instrument performance across a wide range of wind and sea state conditions. Specifically the role of wind speed effects including the rough sea surface and ambient noise contributes to both travel time scatter and modest bias.  An acoustical model reproduced results consistent with our observations.  Inversion of the results to recover internal wave information was evaluated using the Dubreil-Jacotin-Long model and comparisons made with co-located temperature observations (courtesy of Steve Ramp (NPS/MBARI).

(2) Ostrovky's (1978) weakly nonlinear 2-layer rotational theory together with Boyd's (2005) nonlinear stability analysis provided an initial basis for interpreting results of field observations in the South China Sea. The theory evaluates wave evolution in the context of rotational dispersion and nonlinear steepening. The stability analysis illustrates the way in which nonlinearity tends to dominate for the semi-diurnal internal tide across the deep basin of the South China Sea, whereas rotation effectively inhibits steepening of the diurnal component. The theory appears to account for key features of the observations such as the delayed appearance of high frequency nonlinear waves west of Luzon Strait.

(3) Gerkema's (1996) weakly nonlinear 2-layer rotational model allows us to incorporate topography and include internal tide generation. The model was implemented with two ridges in Luzon Strait and illustrates features of the generation and wave evolution, specifically the alternating pattern of high frequency nonlinear wave evolution that occurs during part of the fortnightly cycle. The model provides a convenient basis for evaluating the role of rotational dispersion.  Rotational dispersion plays a major role in modifying the diurnal internal tide in the South China Sea, but has relatively less effect on the semi-diurnal tide.

(4) The fact that our measurements of the internal tide between the two ridges show little sign of nonlinear modification such as steepening or high frequency nonlinear wave development suggests that a linear theory may provide a reasonable representation of the generation process. Hibiya's (1986) two-layer model driven illustrates several features of the observed internal tides, including the consequence of a steady background flow, such as the Kuroshio intrusion. Doppler effects due to flow over the eastern ridge in Luzon could account for the modification of the internal tide so as  to suppress nonlinear internal waves during strong intrusions. By including internal tidal generation at both ridges we find the results qualitatively consistent with observations at our easternmost mooring station A1 in the middle of Luzon strait.

(5) By combining Hibiya's generation model with Helfrich's (2007) evolution model we were able to demonstrate the way in which different tidal forcing conditions accounted for the observed nonlinear internal waves in the deep basin.

(6) In related work on nonlinear internal waves with Kevin Lamb, instability and overturning in a wave observed off the Oregon coast was successfully modeled (Lamb & Farmer, *JPO,* accepted, 2010).
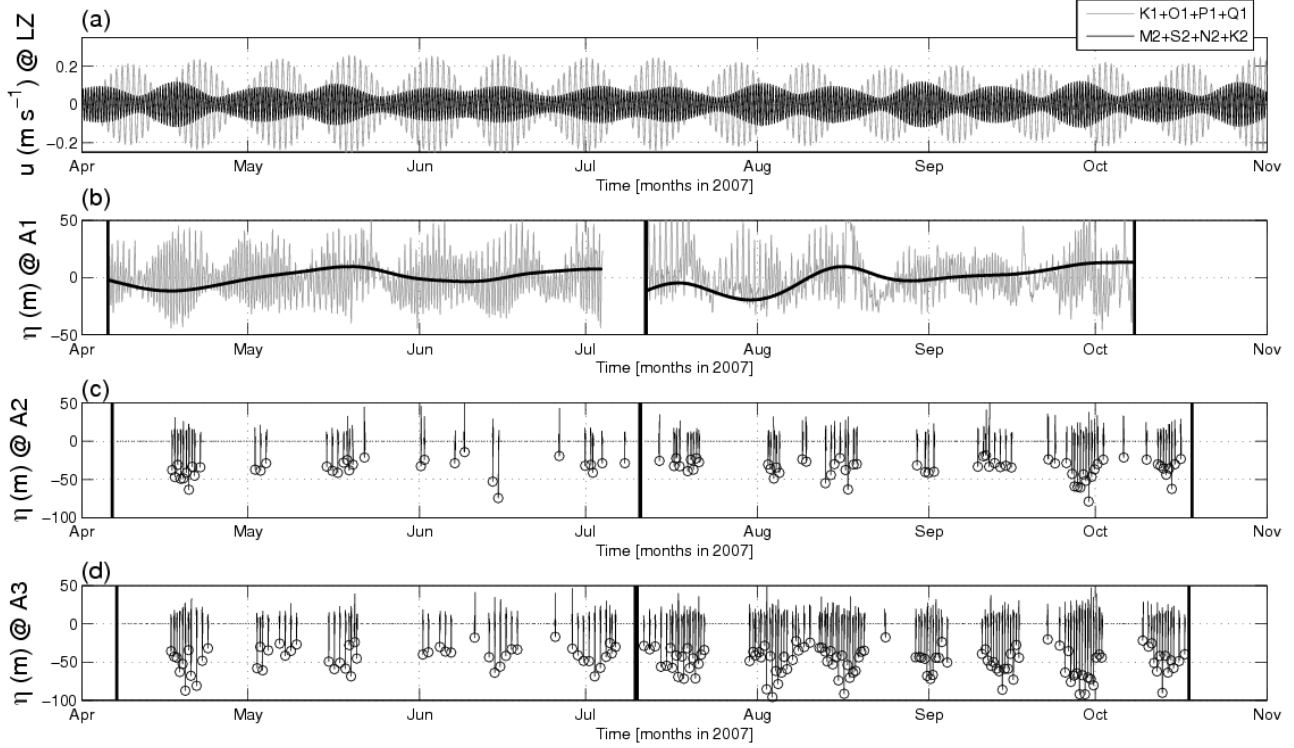
***Fig. 2: (a) Semidiurnal (black) and diurnal (grey) tidal component at Luzon Strait (122°E, 21°N) showing dominance of diurnal signal. (b) Internal waves observed at A1 (subject to 28-day high pass filter). Residual thermocline displacement (black curve) is related to other long time scale oceanic changes. (c) Thin black lines with circles identify high frequency nonlinear internal waves detected at A2. Circle locations indicate the trough of these waves. (d) Same as (c) but at A3. The locations of A1, A2 and A3 are shown in Figure 1. This figure illustrates the intermittency of nonlinear internal waves and their close relationship to semidiurnal tidal forcing.***

## IMPACT/APPLICATIONS

Interpretation of the inverted echo-sounder observations using a sequence of models of graduated complexity provides a framework for identifying the mechanisms by which the well defined high frequency nonlinear internal wave trains are generated, contributing towards a predictive capability. Our results to date, evaluated at a latitude of 21.3N are consistent with the generation of a large amplitude internal tide over the eastern ridge, together with a modest contribution from the western ridge, that evolves under the combined influence of rotation and nonlinearity as it propagates across the deep basin of the South China Sea. Rotational dispersion inhibits steepening of the diurnal internal tide while nonlinear effects dominate evolution of the semi-diurnal signal, accounting for the observed systematic alternation in character of nonlinear internal waves in the deep basin (Fig. 2). Observations at our station between the ridges are consistent with counter propagating internal tides
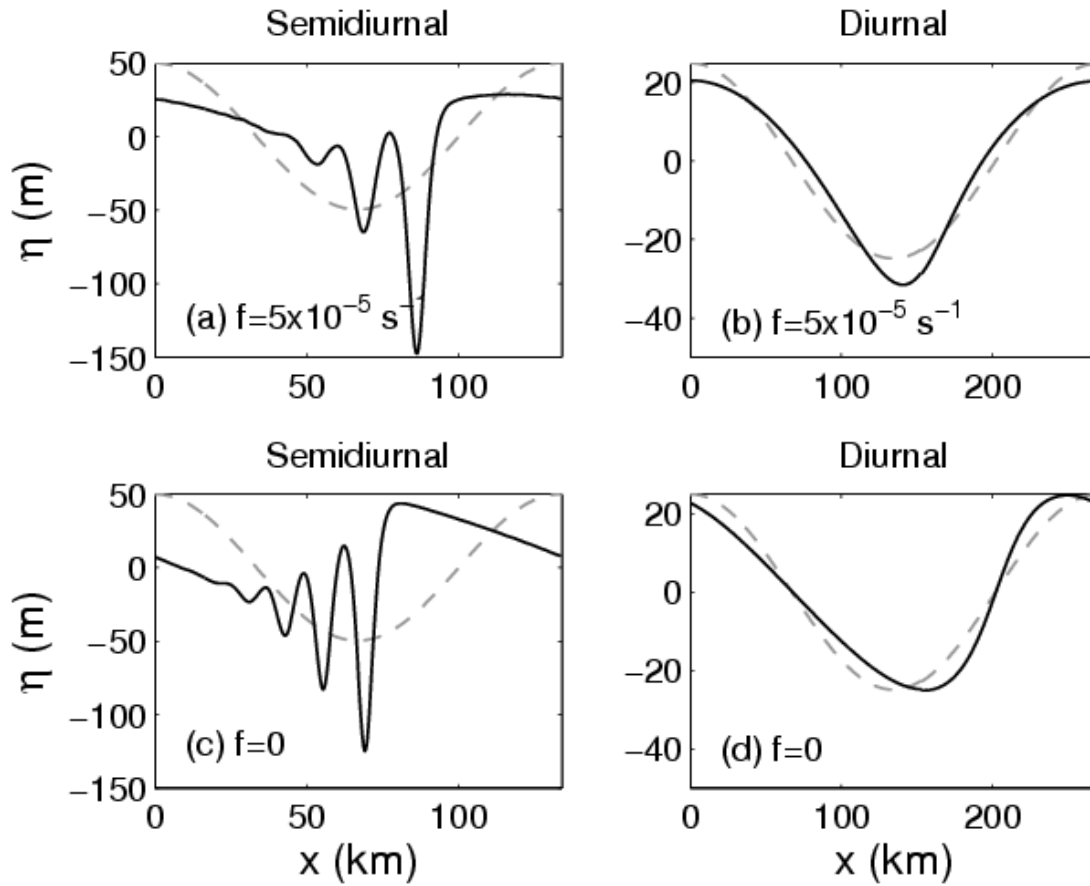
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***Fig. 3: Showing the effect of rotation on internal wave evolution in the fully nonlinear frame. Gray dashed lines: harmonic initial condition, semidiurnal amplitude 50 m, semidiurnal 25 m. Black solid lines: interface after 30 hr evolution, approximate travel time from eastern ridge to station P2 or A3. (a, b) model results with rotation; (c, d) without.***

generated at both ridges; nonlinearity and rotational dispersion are the key factors in modifying the internal tide west of the strait (Fig. 3). The coupled generation-evolution model provides a good prediction of nonlinear internal waves in the deep basin and should provide a reliable set of initial conditions for wave interaction with the slope and shelf region. These results are also proving helpful in planning further measurements under the IWISE program.

**RELATED PROJECTS**

ONR project – IWISE: Internal Waves in Straits

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